Lightweight Thermoplastic Composite Fuel Tanks for Space Applications

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Abstract:
Composite overwrapped pressure vessels (COPVs) have become a critical component in the storage of cryogenic fuels aboard rockets, satellites and spacecraft. Recent research has focused on reducing the cost of COPVs by replacing the inner metallic liner with a low cost alternative, or by removing the liner in its entirety. An integrally heated rotational moulding tool has been constructed and used to produce PEEK polymer liners which have been permeability tested using helium gas. PEEK samples have been overwrapped in a laser-assisted tape placement (LATP) process with a CF-PEEK tape. Cryogenic cycling of liner-overwrap samples has shown crack resistance over multiple cycles. A combined experimental and numerical approach to the design of linerless CF/PEEK LATP composite cryogenic tanks is also presented. Defect characterisation using 3D X-ray CT scanning, optical microscopy and cryogenic cycling has been undertaken. A novel XFEM cohesive zone methodology is used to predict damage in an internally pressurised cryogenic tank, to define an optimised tank lay-up which is resistant to microcrack formation.

Keywords: COPVs, PEEK, Carbon Fibre, Tape Placement, Polymer Liners, Permeability, XFEM, Cryogenic Cycling, X-Ray CT

Introduction

Composite overwrapped pressure vessels have become a critical component in aerospace applications since their initial introduction in the early 1970s [1]. Their ability to store highly permeating fuels at high pressures under cryogenic conditions makes them an integral part of propulsion systems, breathing systems, environmental control systems, and specialised research and analysis equipment aboard rockets, satellites and spacecraft [2]. Recent research has focused on reducing the costs of COPVs by either replacing the standard metallic liner with a low cost polymer liner, or by removing the liner in its entirety, and improving the crack resistance of the carbon fibre overwrap in a linerless COPV design [3-8].

In both cases, the new COPV design must ensure that an adequate level of permeability resistance is maintained while the tank is in operation. COPVs experience an internal pressurisation (5 - 300 bar) and cryogenic temperatures as low as -250 °C during operation, and as such must retain structural integrity while also limiting fuel leakage. These extreme conditions can lead to liner debonding, microcracking and delamination formation within the polymer liner [3, 4] and CFRP overwrap [5-8], which, in severe cases, can result in permeation of the cryogen through the fuel tank walls. Therefore a precise understanding of the material structure and damage accumulation underpins the potential use of these new designs in COPV applications.

In the current paper a modified rotational moulding process is presented as an alternative manufacturing method for thermoplastic polymer (PEEK) liner production [3]. Liner samples, formed using this tooling, have been permeability tested to determine the ability of these materials to store highly permeating fuels. These samples have then been overwrapped in a Laser-Assisted Tape Placement (LATP) process to form liner-overwrap samples for cryogenic testing and X-ray CT scanning tests.

For the linerless tank design, a detailed material and defect characterisation of CF/PEEK thermoplastics was undertaken using optical microscopy and 3-D X-ray CT scanning, as well as cryogenic testing to investigate damage formation in CF/PEEK samples [5]. Resulting material data is used as inputs to a novel XFEM-cohesive zone methodology which is used to predict intra- and inter-ply damage in an internally pressurised cryogenic tank [6-8]. An optimised tank lay-up is presented and tested using the numerical method to ensure both resistance to microcrack formation and fuel leakage through the tanks walls under operating loads [8].

Polymer Lined COPVs

Polymer-lined COPVs have been proposed as a viable alternative to metal-lined COPVs due to their low cost, low weight, resistance to chemical attack, and low permeability characteristics [3, 4]. A modified rotational moulding process (Fig.1) is presented here as an alternative manufacturing method for the production of polymer liners for COPV applications. The modified tooling consists of electrical heating lines dispersed around the metal mould tool, in a segregated pattern, that allows for increased control of temperature distributions across the mould surface. The tool is powered via slip rings at the main rotating joints and the removal of the surrounding oven, common in traditional rotomoulding processes, allows for temperature readings to be taken from multiple locations around the tool. This gives increased control of temperature distributions within the tool and hence increases the dimensional accuracy of the formed part. Multiple prospective liner materials have been tested as part of this analysis with flat panel sections taken from PA11, PA12 and PEEK moulded liners.

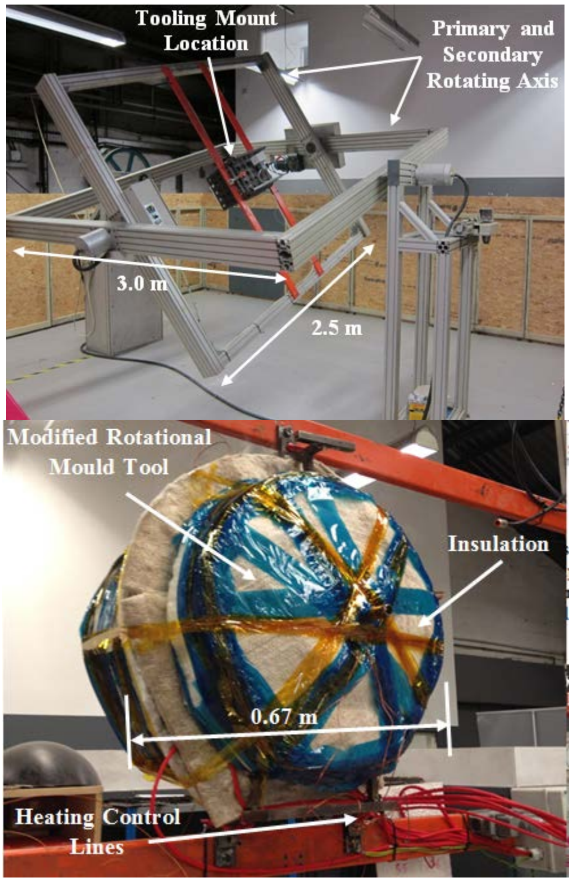

Fig. 1: *Modified Rotational Moulding System and Electrically-Heated Tooling.*

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Flat panel sections have been extracted from the rotomoulded polymer liners for helium permeability testing, to determine if they can achieve the acceptable levels of fuel containment needed for the COPV liners. A helium permeability test rig, following ASTM D1434 [9] and using a Leybold L200 leak detector, has been used to determine the leak rates of all materials. The sample is placed between two aluminium chambers and a vacuum is applied to both sides. The leak detector is then engaged and helium gas is introduced to the upstream side of the sample. The leak rate through the sample is measured over time to determine the steady state leak rate of the sample and its permeability coefficients. Three samples have been tested from each rotomoulded liner.

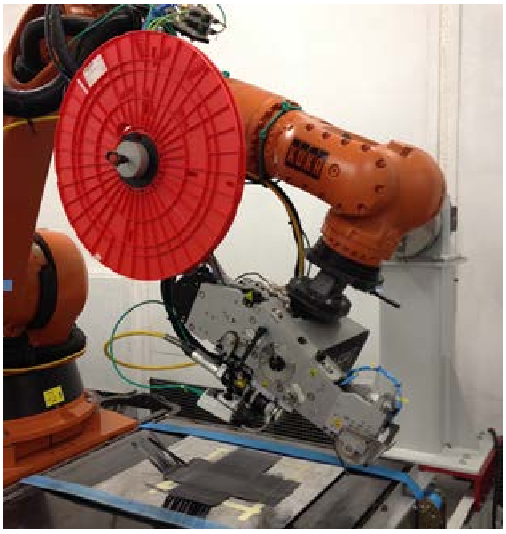

Fig. 2: *Laser-Assisted Tape Placement (LATP) of CF/PEEK Tape over Polymer Liner Samples.*

These samples, once permeability tested, were then overwrapped with a CF/PEEK tape by a Laser-Assisted Tape Placement (LATP) process using a robotic arm and a laser welding head at the ICOMP Centre, Limerick, Ireland, Fig. 2. It uses a 0.125 mm thick by 14 mm wide CF/PEEK thermoplastic tape that is built up on the part over multiple passes and layers to create an overwrapped part. Once overwrapped the parts were thermally cycled in liquid nitrogen and assessed using X-ray CT scanning techniques to map crack growth in the liner-overwrap configuration.

Linerless COPVs

The second part of this research focuses on linerless cryogenic tanks manufactured using the aforementioned LATP unit. A detailed analysis of CF/PEEK laminates was conducted using X-ray CT scanning and microscopy techniques [5]. Samples of different materials, in varying ply thicknesses, were processed in an autoclave and then machined and polished for further analysis. Cryogenic cycling was undertaken in liquid nitrogen, at temperatures near -196 °C, with a 2-15 minute immersion and a 6-30 minute warm up cycle (dependent on the laminate thicknesses). X-ray CT scanning and microscopy were then used to map crack growth over subsequent cryogenic cycles.

The results from this experimental analysis were then used in a combined XFEM cohesive zone model for predicting three-dimensional microcracking and permeability in composite laminates [6, 7]. The microcrack initiation is predicted using the XFEM methodology while the mixed mode cohesive zone model controls the delamination, Fig. 3. Random microcrack initiation was modelled using a Weibull distribution of fracture strengths. The permeability of these laminates, based on crack opening displacements and the dimensions of leak paths, were then assessed in comparison to measured results for various CF/PEEK materials.

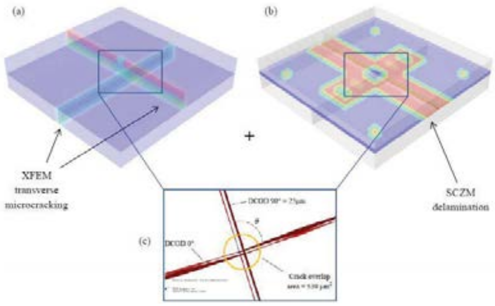

Fig. 3: *XFEM Cohesive Zone Model for Microcracking and Delamination Analysis [7].*

Finally, a combined experimental and numerical assessment of tape-laid CF/PEEK laminates was undertaken using the previously defined testing and model analyses. Tape-laid CF/PEEK laminates were assessed using X-ray CT scanning and microscopy after cryogenic cycling, the resulting data was input into the novel XFEM-cohesive zone methodology, and an optimised tank lay-up was defined [8].

Results

The modified rotational mould tooling has shown success in moulding polymer liners of various materials, Fig. 4. The use of segregated heating has also proven valuable as heat losses in the flange region are significant, and as such, preheating the flange region has improved wall thickness distributions in formed parts, (distance marker of 300 mm in Fig. 5) [10]. The subsequent permeability tests have shown that the formed polymer liners (≈ 3 mm thick approximately) are capable of reaching the low permeability requirements required for COPV applications, Table 1. The LATP overwrapping process was successful for overwrapping PEEK polymer liners. These overwrapped PEEK liners were then cryogenically cycled in LN_2 to determine their resistance to cracking in cryogenic

Fig. 4: *A Rotomoulded PEEK Demonstrator Liner.*

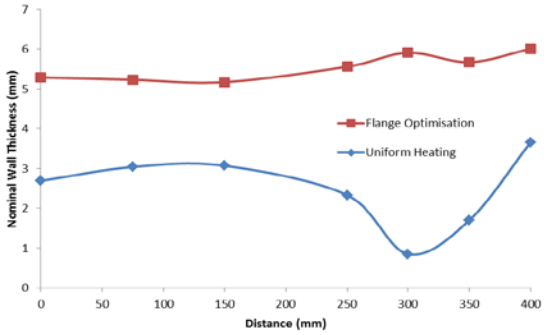

Fig. 5: *Wall Thickness Variations in the Formed Polymer Liner.*

Table 1: *Permeability Results for Rotationally Moulded Polymer Liners.*

Sample	Leak Rate (10^{-5} scc/ m^2.s)	*P* (10^{-7} scc .m /m^2.s. bar)	*D* (10^{-10} m^2/s)	*S* (10^3 scc/m^3 bar)
PA12	26.1	6.89	3.86	1.8
PA11	9.82	3.29	2.32	1.41
PEEK	46.3	11.7	1.56	7.69

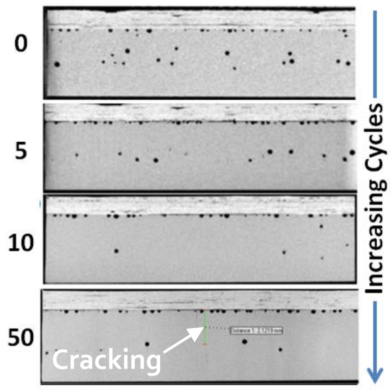

Fig. 6: *X-Ray CT Image Showing No Cracks in CF/PEEK (upper skin)-PEEK Liner (lower) Samples after 10 Cycles and Cracking after 50 Cycles.*

environments. Results have shown crack resistance for up to 10 cryogenic cycles with cracking occurring after a further 50 cycles, Fig. 6.

The linerless studies have also highlighted a number of issues with CF/PEEK laminates and their abilities to store cryogenic fuels. From an analysis of CF/PEEK samples after cryogenic cycling, it was found that thicker laminates (32 plies) experienced extensive damage in comparison to thinner laminates (8 plies) which experienced little to no damage [5]. This was attributed to larger residual stresses in the thicker laminates. Through-thickness microcrack networks were more apparent in quasi-isotropic laminates, indicating a poorer level of permeation resistance, Fig. 7. The majority of damage was observed to occur after the first cryogenic cycle.

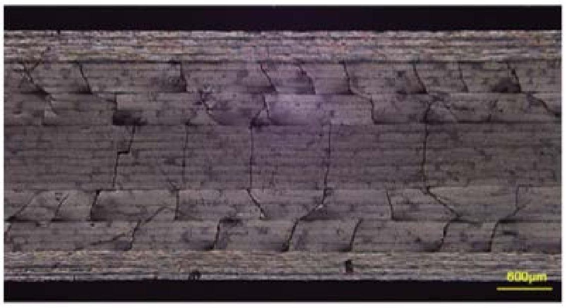

Fig. 7: *Microcrack Networks through the Laminate Thickness in an Autoclaved 32-Ply CF/PEEK Quasi-Isotropic Laminate.*

These results were used to develop the XFEM-cohesive zone model, along with intrinsic material property data for CF/PEEK materials, showing that the model was capable of predicting crack growth in complex three-dimensional networks and allowed for direct computation of crack opening displacements and resulting permeability analyses [6, 7]. The predicted crack networks were consistent with 3D X-ray images taken of actual CF/PEEK laminates.

This modelling was then applied to LATP CF/PEEK tanks, with material property assessments of LATP CF/PEEK used to model the optimal design of the tank overwrapping sequence with the developed XFEM-cohesive zone methodology. X-ray CT assessments of LATP CF/PEEK have shown that the void and defect contents of the LATP samples are an order of magnitude higher than their autoclave counterparts [5, 8]. A detailed tank design was developed to reduce the transverse stress through the tank wall, with the aim of reducing thermal residual stress build-up which can cause extensive microcracking in the wall cross section. The results showed that a combination of hoop and high-angle helical plies reduced transverse stress levels, which has an improved crack resistance over traditional COPV lay-ups, as shown in Fig. 8.

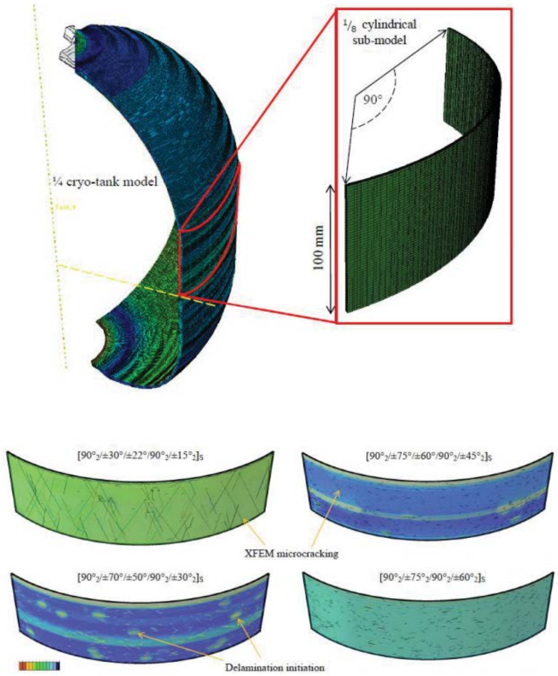

Fig. 8: *Microcrack Networks in COPV layups with the lowest crack density formation in high angle ply layups (bottom right image) [8].*

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